03/0393"

A Survey of Low Frequency (LF) Waves at Jupiter: The Ulysses Encounter

Bruce T. Tsurutani[1]
David J. Southwood[2]
Edward J. Smith[1]
Andre Balogh[2]

[1]Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

[2]Imperial College of Science and Technology
The Blackett Laboratory
Prince Consort Road
London SW7 2 BZ
England

ABSTRACT

We report the results of a survey of Low Frequency (LF) plasma waves detected during the Ulysses Jupiter flyby. In the Jovian foreshock, two predominant wave periods are detected: 10^2s and 5s, as measured in the spacecraft frame. The 10^2s waves are highly nonlinear ($\Delta\vec{B}/B_0 \approx 1.5$), propagate, at large angles to $\vec{B}_0$ (typically 50°), are steepened, and sometimes have attached whistler packets. For the interval analyzed, the 102s wave.s had mixed right- and left-hand polarizations. We argue that these are all consistent with being right-hand magnetosonic waves in the. solar wind frame. The 1 (Ps waves with attached whistlers were similar to cometary Waves. The trailing portions were linearly polarized and the whistler portions circularly polarized with amplitudes decreasing linearly with time. The emissions are generated by ~ 2 keV protons flowing from the Jovian bow shock/magnetosheath into the upstream region. The instability is the ion beam instability. Higher Z ions were considered as a source of the waves, but have been ruled out due to the low sunward velocities needed for their resonance. The 5s waves have ($\Delta\vec{B}_0/B_0 \approx$ **0.S)** are compressive and are left-hand polarized in the. spacecraft frame. Local generation by three different resonant interactions were considered and have been ruled out. One possibility is that these waves are whistler mode by-products of the steepened lower frequency magnetosonic waves. Mirror mode structures were detected throughout the outbound magnetosheath passes. θ_{kB} for these structures were consistently in the range 80<' to 90°, exceptionally high values. Assuming 1 keV protons, the spacing between the magnetic decreases is - **10-201',).**. Close to the magnetopause, small amplitudes $\Delta\vec{B}/B_o \approx 0.15$), transverse waves were detected. Within the wave packet, right-, left- and linear polarizations were found. These may be similar 10 wave.s detected in the Earth's Plasma Depletion Layer (PDL). Within the Jovian low latitude boundary layer, enhanced transverse spectral power was detected at frequencies just below the proton cyclotron frequency. A total magnetic power of 10^{-1} nT^2 was determined. Cross-f -field diffusion of - 1 keV protons yields a calculated boundary layer thickness of 0.15 R_J; if 100 keV magnetospheric protons are assumed, a 1.4 R_J thickness can be

formed by this process. Transverse left-hand (spacecraft frame) waves were detected within the Jovian magnetosphere. These waves have periods of 5-8 minutes, are elliptically to circularly polarized and propagate in a range of 10° to 43° relative to $\vec{B}_0$. It is most likely that these waves are generated by an ion beam instability. Assuming S^{+}, we get a resonant parallel energy of 60 keV.

INTRODUCTION

Previous spacecraft encounters with Jupiter have indicated the presence of Low Frequency (LF) electromagnetic waves in and near the Jovian Magnetosphere (Smith, et al., 19-/6; Smith et al., 1983; 1984; Smith and Tsurutani, 1983; Goldstein et al., 1983; 1985; 1986, Smith and Lee, 1 986; Glassmeier et al., 1 989). in this paper we will survey LF waves detected by the magnetometer onboard the Ulysses spacecraft during its near-Jupi(cr swingby in February 1992. The purpose of this paper will be to give the results of a preliminary survey of waves in the Jovian foreshock, magnetosheath, low latitude boundary layer and magnetosphere. Many of these LF wave modes have never been observed previously at Jupiter. Analogous waves have, however, been reported in the near-Earth environment. Comparisons of wave properties and wave-partic]c interactions in the two regions will be made where appropriate.

Ulysses was launched from Cape Kennedy on October 6,1990 on a mission to explore. the polar regions of the Sun. In order to obtain a trajectory with > 70° solar latitude.s, it was necessary to first send the spacecraft to Jupiter to obtain a gravitational assist to fling Ulysses well out of the ecliptic plane. The planetary encounter (perijove) occurred on February 8, 1992 (1204 UT). The near-Jupiter trajectory is shown in Figure 1. One unique feature of the flyby was the probing of the (iusk-side magnetosphere/magnetosheath, a region which had not been previously explored (Smith et al., 1992). In their initial report (Balogh et al., 1 992a), magnetic field investigators noted intense LF waves within this region. We will analyze these waves as well as others detected during the inbound pass.

The magnetometer investigation has been discussed in detail in Balogh, et al. (1992 b). The instrument is composed of a Vector Helium magnetometer and Fluxgate magnetometer. One magnetic vector per second is obtained from each sensor, This high time resolution data will be used in this paper.

APPROACH

To survey the LF waves ($f < 1$ Hz) within and in the vicinity of the Jovian magnetosphere, a systematic scan of magnetic field data for the entire encounter period was made. The highest time resolution (1 s) data was utilized so that possible high frequency emissions would be detected as well. This paper reports all of the obvious emissions detected during the Ulysses encounter. There is, however, the possibility that some waves were either overlooked or missed in this survey.

RESULTS: OBSERVATIONS

Foreshock

The magnetic field in the region upstream of the bow shock (the foreshock) is shown in Figure 2. The field is plotted in Solar Heliospheric (SH) coordinates where R is radially from the Sun, T is $\hat{R}$ crossed into the solar rotation axis, $\hat{\Omega}$, (normalized), and $\hat{N}$ completes the right-hand system. This foreshock region is distinguished by the presence of large amplitude compressional waves with periods of $\sim 10^2$ s and occasional wave packets that have cycles with ~ 25 s periods. Two examples of the latter are found in this Figure, one at 1705 UT and a second at]-/12 UT.

The low frequency (10^{-2} Hz) compressional waves can have peak-to-background ratios as large as three-to-one and peak-to-peak transverse amplitudes as large as 1.5 times the background field, i.e., the waves are highly nonlinear. 'll w--- 25s wave packets are also highly nonlinear at times. The event at - 1705 UT has a peak-m-peak transverse amplitude. at 1.4 nT in a 0.6 nT magnetic field.

Principal axis analyses (Smith and Tsurutani, 1976) were performed on the wave.s of this Figure. The intervals of analysis arc indicated by horizontal bars at the bottom. The results of the analyses arc indicated in between the B_z and $|B|$ panels. Given arc the angles of propagation of the wave relative to the ambient magnetic field, θ_{kB}, and also the wave sense of rotation relative to $\vec{B}_0$. R indicates a right-hand sense of rotation and 1, stands for left-hand rotation (as measured in the spacecraft frame). We find a mix of polarizations, both right-hand and left-han(i in this interval. The waves propagate at relatively large angles relative to the ambient field, varying between ?4" and 84°. No waves were found which were. propagating at angles less than 15". The waves varied from circularly to elliptically polarized. Most were plane polarized, but some were not.

A relationship between the wave. polarization and the magnitude of B_x is apparent in the Figure. The three intervals where the waves are left-hand polarized arc cases where B_x is large, and the cases where the waves are right-hand polarized are uses where B_x is small. The field magnitude varies **throughout** the interval, but is constant within a factor of 2 to 3. In this coordinate system, the former corresponds to times where the magnetic field is aligned along the solar wind velocity vector (close to the - $\hat{x}$ direction) and the latter when the field is orthogonal to the solar wind direction. This variation in the field alignment has important consequences in the Doppler shift of the waves. This will be discussed later.

We now examine the wave cycle that occurs between 1702 to 1707 UT. The average property of the wave is that it is left-hand polarized and is propagating at an angle of **24”** relative to $\vec{B}$. We **have,** however, also broken the wave into two parts, 1702 UT **-1704** UT **and** 1704-1707 UT. Principal axis analyses were performed on these two pieces and the resultant hodograms are indicated in Figure 3. The B_1 coordinates are the principal axes where B_1 is the direction of maximum variance and B_2 is the direction of intermediate variance. B_3, the direction of minimum variance, or the direction of wave propagation, is out-of-the-paper, and completes the right-hand system.

The left-hand panels indicate that this first portion of the wave is linearly polarized (λ_1/λ_2 = 14.6). The direction of minimum variance (θ_{kB}) is along the field, consistent with this portion being purely compressive. The right-hand part of Figure 3, is the hodogram for the high frequency packet portion of the wave. In this event, the magnetic field is out-of-the-paper, indicating that this portion of the wave. is left-hand circularly polarized in the spacecraft frame. The wave packet is plane polarized (not shown) and is propagating at an angle of 30° relative to the upstream ambient magnetic field. The wave packet is compressional as indicated by the field magnitude variations shown in the Figure.

It is noted from the Figure 2 that the high frequency wave packet starts with a large amplitude and this amplitude, decreases with time. From previous foreshock and cometary waves, we know that these packets form al the leading edges of steepened waves and the packet amplitudes decrease in the direction of propagation. This indicates that this wave is intrinsically right-handed and are propagating against the solar wind, but are convected downstream. This is consistent with the picture of wave generation by ion beams flowing in the sunward direction.

Another type of wave detected in the foreshock is shown in Figure 4. These are high frequency oscillations superposed on top of the 10^{-2} Hz waves. These waves have frequencies near 2 x 10^{-1}

Hz and are left-hand polarized in the spacecraft frame. The peak-to-peak transverse amplitude is $\Delta\vec{B}/|B|$ -(). S with a significant compressional component, $\Delta|B|/|B| \approx$ ().2. One noteworthy feature is that the largest wave amplitudes are often detected when the magnetic field magnitudes is al a local maximum. This can be noted in the bottom panel of the Figure. Examples can be found at 1535, 1541, 1547, **602,** 1604 and 1616 UT.

Magnetosheath

a) Mirror Modes

Large magnetic structures were detected in the outbound magnetosheath, but not the inbound magnetosheath (the cause for this difference will be explored later in the Discussion section). An example of these outbound magnetic structures is given in Figure 5, in SH coordinates. The mirror mode structures are the fine scale oscillations in the |B| pane]. '1'here are little or no variations in the two angle plots. The data has been illustrated in spherical coordinates because the above features (little or no angular variations) is one. characteristic of this particular mode (Tsurutani et al., 1 982). Balogh et al. (1 992) noted that this is perhaps the longest train of "waves" ever observed in the history of space plasma observations.

These magnetic structures extend essentially throughout the entire Jovian magnetosheath. An outer magnetosheath discontinuity is crossed al - 1710 UT February 13, 1992, shown on the right of the Figure, and several magnetopause crossings arc on the left at -- 1357, I **740** and - 1910 UT February 1 **2.,** 1992 (Bame et al., **1992a). It** is noted that the mirror mode structures have the smallest amplitudes near the bow shock and the largest amplitudes near the magnetopause. This would be expected if these structures are generated by a convective instability, where the instability starts near the discontinuity and continues to develop as the structure.s are transported towards the magnetopause. These magnetic field lines on the flank of the magnetosheath arc simply a projection of the subsolar magnetosheath fields as they drape around the magnetosphere (Tsurutani et al., 1982).

An example of the mirror mode structures given in high resolution (1s) is shown in Figure 6. This hour interval from 2100102200 UT is relatively close to the magnetopause at 1910 UT, shown in Figure 5. The peak-to-minimum field values vary from 3-to-1 to 4-Lo-1 and the separations between the field minimum vary from 1-1/2 min near 2100 UT to ~ 1 min near **2140** UT.

If one assumes -1 keV magnetosheath protons, the scale size between the magnetic decreases is 10-20 proton gyroradii. This value is calculated by equating the scale to the measured magnetosheath convection velocity times time. Principal axis analyses have been performed on tens of these structures. It is found that the angle between the minimum variance direction and $\vec{B}$ consistently varies from 80° to 90°, values which are exceptionally high. From our survey, this direction ($\vec{k}$) was never found to be less than 80° relative to the ambient magnetic field. We have only examined the most developed waves (largest amplitude) to date, however.

b) Transverse Modes

Some discrete transverse wave modes were detected in the Jovian magnetosheath on the inbound passage. The small amplitude wave train is shown in Figure 7. This is the first time such waves have been reported at Jupiter. The peak-to-peak transverse amplitudes are - $\Delta\vec{B}/|B| \approx 0.15$, with little or no compressional $\Delta|B|/|B|$ component. The wave period is -30- 50s in the spacecraft frame. in a 5 nT field, this corresponds to frequencies of 0.25 -0.45 Ω_p (without the Doppler-shift removed, however).

Analyses of the wave polarization have been made using the principal axis analysis technique described previously. An example of a hodogram of one wave which occurred from 1859:10 to 1859:51 UT is shown in Figure 8. This wave is left-hand circularly polarized in the spacecraft frame and is propagating, at an angle of 33° relative to $\vec{B}_0$. The large ratio of $\lambda_2/\lambda_3 = 9$ indicates that the wave is plane polarized.

All of the wave cycles within the packet have been analyzed. It is found that the polarizations are highly variable. One wave cycle was found to be essentially linearly polarized ($\lambda_1/\lambda_2 = 29$) propagating at an angle of 87° to $\vec{B}_0$. Other wave cycles were right and left-hand polarized in the spacecraft frame and were propagating at more modest (19° - 23°) angles relative to $\vec{B}_0$. A discussion of the significance of these highly variable polarizations and $\vec{k}$ directions will be postponed until the Discussion section.

Boundary Layer

A magnetopause boundary layer has been discovered at Jupiter, identified by unique thermal plasma characteristics (see Bame et al., 1992a). Because of the highly fluctuating position of the magnetopause due to solar wind ram pressure variations, the magnetopause/boundary layer was crossed several times on both the inbound and outbound portions of the trajectory. We have studied all of the major boundary layer regions using power spectral analyses to determine if enhanced wave activity is present.

Figure 9 illustrates one of the spectra taken at 2135-2159 UT, February 2, 1992. This interval occurred on the inbound passage. The coordinate system used is a field-aligned system where B_x is oriented along the average magnetic field direction. $\hat{B}_z$ is B_x crossed into the Sun-Jupiter direction (normalized) and B_y completes the right-hand system. This system has been chosen to illustrate the compressional nature (or lack thereof) of the waves present. In the Figure, it is

noted that B_x and |B| have nearly identical traces. This indicates that there was not much variation in the magnetic field direction during the interval and B_x is a reasonably accurate representation of this value. Thus, B_y and B_z can be regarded as transverse fluctuations present within the boundary layer.

The proton cyclotron frequency Ω_p, is indicated in the Figure. One can note an enhancement of transverse wave power in the B_y and B_z plots at frequencies slightly below Ω_p. This same genera] feature was noted in all four boundary layer intervals studied. The local peak in the power spectrum at -2 x 1(1-2 Hz is -1 nT^2/Hz. Multiplying by a conservative bandwidth of 1()-1 Hz gives $B_w^2 \cong 10^{-1} nT^2$.

Magnetosphere

Waves were sought within the magnetosphere. No obvious emissions were found in association with the L shells of the Jovian satellites, as they had been previously (Smith and Tsurutani, 1983). The only clear example of waves arc shown in Figure 10, an example found in the outbound passage when Ulysses was in the dusk sector.

These waves have relatively long periods, 5-8 minutes in duration. The amplitudes arc again quite small. Peak-to-peak transverse amplitudes arc $\Delta\vec{B}/|B| \approx$ (). 1. One can no(c that the waves arc almost purely transverse, with little or no compressional components.

Figure 11 illustrates one cycle of the wave at 1445:51 **-1457:10** UT, illustrated in principal axis coordinates. The wave is nearly circularly polarized, propagating at an angle of 25° relative to tie. The B_1 - B_3 and B_2 - B_3 hodograms indicate that the wave is not plane polarized, however.

All of the other wave cycles of the packet were analyzed. It is found that all arc left-hancl elliptically to circularly polarize.d. Their angles of propagation vary from θ_{kB} = 1 O“ 1043°.

DISCUSSION

Foreshock Waves

a) f $\simeq 10^{-2}$ Hz Waves

The presence of waves well upstream of the nose of the Jovian bow shock is a surprise, as the interplanetary magnetic field at 5 AU should bc quite tightly wound up. ‘1’bus, one would normally expect a quasiperpendicular shock at Jupiter’s subsolar point with little or no upstream waves. in this case, the interplanetary magnetic field was directed along the Sun-Jupiter line, an unusual orientation. The cause for this unusual directionality (and also the low solar wind ram pressure reflected by the large extent of the bow shock - Smith et al., 1992) is that Ulysses encountered the bow shock at a time when a trailing portion of a Corotating Interaction Region (CIR - Smith and Wolfe, 1976), was just upstream of the shock. This IMF orientation allowed the flow of energetic particles brick into the upstream solar wind and through plasma instabilities, the generation of the I ,F waves.

The mix of wave polarizations, both right-hand and left-hand, were noted to be ordered by the direction of the ambient magnetic field. The waves were ri[:ht-handed when the magnetic field was more orthogonal to the solar wind direction. For a pure] y orthogonal magnetic field, there is no Doppler shift and the frequency and sense of rotation as measured by the spacecraft magnetometer could be the same as in the plasma frame. ‘1’bus, these particular waves arc most probably right-hand magnetosonic waves with plasma frame frequencies c1osc to - 10-21 Iz.

An important clue to the plasma frame polarization of the left-hand polarized waves and their direction of propagation is given by the example shown in Figures 2 and 3. In this event, the high frequency packet is found in the trailing portion of the longer period (10-2 Hz) waves. 'l'his is consistent with the lower frequency wave plus higher frequency packets propagating into the upstream direction (in the plasma frame), but due to the higher speed of the solar wind, the waves are convected back across the, spacecraft by the solar wind. These waves would then be right-hand polarized in the plasma frame. Thus all of the waves in Figure 2. arc consistent with being right-hand polarized in the solar wind frame.

The same instability and nonlinear waves have been noted in tile Earth's foreshock and at comets, (Gary, 1991; Tsurutani, 1992). This type, of ion resonant instability has been observed to dominate LF waves generated in the Earth's foreshock (Tsurutani and Rodriguez, 1981; Hoppe et al. 1981) and at comets (Tsurutani, 1991). The ion beams resonate with right-hand cyclotron waves which arc propagating into the upstream direction. The ions overtake the waves, anomalously sensing them as left-handed (the same sense of rotation as the ion gyration about $\vec{B}_0$), and cyclotron resonance takes place (Thorne and Tsurutani, 1 98'/; Gary 1991).

Assuming this instability, the energy and specie of the responsible ion beams can be calculated. We first consider protons as the responsible particles. '1'0 determine the energy 01 the resonant ions, we must first determine the wave frequ ency in the plasma (rest) frame. The solar wind had a velocity and density of 500 km s^{-1} and 7×10^{-2} cm^{-3} at the time of the Figure 2 waves, respectively (Bame et al., 1992a). We assume $V_{ph} \cong V_A$ (tile wave.s arc quite nonlinear, so this may not be totally correct, but should be accurate within a factor of 2). Using a simplifying assumption that $\vec{k}$ is along $\vec{B}_0$, it can be determined that the wave frequency in the solar wind is $\cong 2 \times 10^{-4}$ Hz. (If $\theta_{kB} > 0$, the rest frame frequency is higher and the particle resonant velocity is lower). I 'rem tile cyclotron resonance condition:

$$V_{\|} = V_{ph} (1 - \Omega_i/\omega) \tag{1}$$

it is determined that the parallel kinetic energy for resonant protons is ~ 7 keV. If the wave phase velocity is higher, the resonant energy will be higher. It should be noted that the above proton energy is given in the solar wind frame. As stated previously, the solar wind velocity at this time was 500 km s-1. Such protons thus have velocities of ~ 650 km s^{-1} relative to the spacecraft. This corresponds to a proton energy of 2.2 keV in **the** spacecraft frame. This is quite consistent with these particles being (slightly energized) solar wind protons reflected off of the Jovian bow shock or magnetosheath protons escaping into the upstream region.

We have also examined the possibility that the waves could be due to heavy ion beams, perhaps particles that have diffused from the Jovian magnetosphere to the magnetosheath via scattering in the boundary layer (to be discussed later) and then into interplanetary space. From equation (1) the parallel velocities of such resonant ions can be easily calculated. It is found that the ion velocities are too low to flow into the upstream dire.ction without being convected downstream, so the possibility of magnetospheric high Z particle leakage as a source of these waves can be ruled out.

Previous discussion of the Jovian foreshock LF waves led to a great dea of discussion concerning the responsible charged particles. Both relativistic electrons of Jovian origin (Smith et al., 1976; Goldstein et al., 1985), Jovian protons (Smith et al., 1983; 1 984; Goldstein ct. al., 1983), and Jovian sulfur and oxygen ions (Goldstein et al., 1986) have been proposed and considered. The problem lies in the knowledge of the plasma frame wave polarization and direction of propagation. Without these pieces of information, the question cannot be easily resolved. If the waves are left-hand polarized in the plasma frame propagating into the upstream direction, the.n the resonant particle beam are only be electrons (assuming the particle source is the bow shock or magnetosheath). If the waves are intrinsically right-hand polarized propagating in the upstream dire.ction, then the resonant par-ticks are protons or heavier ions. For Ulysses, we find for one. interval analyzed, the upstream waves arc right-handed in the solar wind frame and arc propagating into the upstream direction, allowing us to determine that ions (2.2 keV protons) were. responsible for this particular event.

The wave polarization in this interval often varied from cycle.-to-cycle. This Change, presumably in the Doppler shift conditons, was caused by variations in the direction of the ambient magnetic field. When the wave fields arc comparable to the ambient field, as was the case here, the waves themselves can cause these field directional fluctuations. ']'bus, we emphasize that in situations of this type (existence of nonlinear waves), exceptional care must be taken to extract the Doppler shifts. Waves must be examined from cycle-to-cycle, one at a time. Multiple wave. cycle analyses may obviously give misleading and possibly incorrect results.

It should be noted that other foreshock intervals are available in the Ulysses Jovian data set for analysis. Preliminary looks indicate. that both left-hand and right-hand polarized waves are present as was the case here. Whether all of the.sc waves arc consistent with being right-handed in the solar wind frame or not, has not been determine yet. Further detailed analyses arc needed to answer this question. This will be the subject of a future short report.

We note that the nonlinear evolution of the waves arc quite similar to those at Comet Giacobini-Zinner (Tsurutani, 1991). The magnetosonic waves steepen, form a trailing "linear" compressive portion and arc sometimes led by a large. amplitude whistler packet. The whistler wave amplitude. decreases linearly with time (and distance).

$f \sim 2 \times 10^{-1}$ Hz Waves

We consider three potential resonant instabilities or the local generation of these foreshock waves (found everywhere in the upstream region): 1) the waves are left-ban(i polarized in the plasma frame, and arc propagating in the solar wind direction; 2) the waves arc right-hand polarized in the plasma frame, but arc propagating towards the sun (wc will consider ion beams as the. source), 3) the waves are right-handed in the plasma frame, propagating toward the sun (wc. will consider electron beam as the source).

Each of these three possibilities can be ruled out with further consideration. For case 1), if we assume the waves arc propagating parallel to B_0, the Doppler shift can be removed. We find that these waves would have plasma frame frequencies of f_{sw} = 1.6 x 10^{-} Hz, a frequency which is above the local proton gyro frequency. Electromagnetic waves with this properly do not exist and can be ruled out. For condition 2), we find that the waves would have a frequency of 1.8 x 10^{-2} Hz in the plasma frame. Any ion species resonant with the. waves will have parallel velocities far too low to propag ate upstream against the solar wind. Thus, possibility 2) can be ruled out. For scenario 3), the energetic electrons would have to be streaming toward the Jovian bow shock. The only source of such energetic electrons would be solar flare particles or electrons generated by an interplanetary shock upstream of Jupiter. 1 ilectrons from either source have not been detected to date for this even t, however.

The three obvious sources of local wave generation by resonant interactions have. been ruled out. Another potential source. is generation by a nonlinear steepening process. The 1 0^{-2} Hz low frequency waves steepen and form the upstream whistler packets shown in the insert of Figure 2. It is thought (Omidi and Winske, 1990) that these whistlers are simply dispersive waves generated by the steepening process. The eventual fate of such packets is presently unknown. These whistlers may detach and propagate into the interplanetary medium. Simulations such as those of Omidi and Winske (199(1) have indicated that such a scenario may occur. Because these high frequency waves are associated with regions where the magnetic field magnitudes are the largest, the observations are. consistent with this idea. in this scenario, the waves are whistler mode emissions with frequencies of - 1.8 x 10^{-2} Hz propagating towards the sun. These emissions are convected past the spacecraft by the solar wind and are detected as left-hand polarized in the spacecraft frame.

Magnetosheath Structures and Waves

The condition for mirror mode instability is:

$$\beta_\perp/\beta_\parallel > 1 + 1/\beta_\perp \tag{2.}$$

The mirror instability occurs when the pressure anisotropy, $\beta_\perp/\beta_\parallel$, is either large or when $\beta_\perp/\beta_\parallel > 1$ and β is high. This instability was originally discussed by Chandrasekar et al. (1958), then by Hasegawa (1969, 1975), and more recently by Patel et al. (1983), Price (1986), Migliuolo (1986), Lee et al. (1988), Price. (1989), Gary (1992), Gary et al. (1992) and Southwood and Kivelson (1992.). From the above expression for instability, it can be noted that when β is high, the instability can occur for relatively small anisotropies, such as in a shocked plasma, e.g., within a planetary magnetosheath (Tsurutani et al., 1982, 1984; Thorne and Tsurutani, 1981, Croley et al., 1986), in a cometary magnetosheath (Smith et al., 1987; Yeroshenko, c1 al., 1987; Russell et al., 1 987) or in the solar wind al stream-stream interaction regions (Tsurutani et al., 1987b; 1992).

For planetary magnetosheaths, the necessary pressure anisotropies can be created when the solar wind plasma is abruptly decelerated and preferentially heated (in '$T_\perp$') across a perpendicular shock. The anisotropy will be further enhanced as the plasma and magnetic fields drape around the planetary magnetosphere as the magnetosheath plasma convects towards the dayside magnetopause, as described by the Zwan-Wolf (1976) model. Thus, if the interplanetary magnetic field is oriented orthogonally (or nearly orthogonally), free energy for the mirror instability is supplied all the way from the shock to the magnetosphere. A schematic of this is illustrated in Figure 12. The figure shows sheath fields and post-shock plasma distribution functions for interplanetary fields both perpendicular (a) and parallel (b) to the solar wind velocity.

On the Ulysses inbound passage, the interplanetary magnetic field was directed toward the Sun (radial) and the plasma hinting at the shock nose was that of a quasiparallel shock where the ions were presumably heated primarily in the field-aligned direction (shown in Figure 12b). This anisotropy is not conducive to the. generation of mirror mode structures and none were detected. Ten days later, as Ulysses was exiting the magnetosphere, the interplanetary magnetic field had returned m its more typical tightly wound Parker spiral configuration (Lepping et al., 1993) and a quasiperpendicular shock would have formed near the nose of the bow shock. Because the pressure anisotropy is initially formed at the shock and is enhanced as the plasma and field lines convect towards (and drape around) the magnetosphere, one would expect the mirror structures to continually grow as the magnetosheath plasma is convected from the shock to magnetopause. The relationship between the field and plasma near the subsolar point to that at the flanks near local dusk is illustrated by Figure 12a. For this interplanetary field configuration the mapping from noon to dusk local times is quite simple. The results presented in this paper are consistent **with** the above scenario.

There has been quite a bit of controversy as to why mirror mode structures are detected in the planetary magnetosheaths when the linear growth rate of ion cyclotron waves is theoretically greater (Price et al., 1986; Gary, 1992). The most recent work of Gary et al. (1992), indicates that for small anisotropies, $2 > T_\perp/T_\parallel > 1$ in high β plasmas ($\beta > 1$), the mirror mode has the highest growth rate, but for low β plasmas, the ion cyclotron has the highest growth rate. 'I'his new result seems to explain the various observations.

In addition to mirror mode structures, transverse waves have previously been reported in planetary magnetosheaths (Fairfield and Behannon, 1976; Hubert et al., 1989, Sckopke et al., 1990; Brinca et al., 1990; Gleaves and Southwood 1990; 1991). Most recentl y, waves have been identified and studied in the plasma depletion layer (PDL), a region of low β plasma adjacent to the magnetopause. Song et al. (1990) find that the waves during their event are either right-hand or linearly polarized. The center frequency of the waves is about $0.5\Omega_i$ and the compressional component is about 10% of the ambient field strength. Because the waves arc not left-hand polarized, they argue that the waves are not ion cyclotron waves and their generation may be associated with the free, energy of the stro ng gradients present in the region. On the other hand, Anderson et al. (1991) have found waves in the same region of space using tile AMPTE/CCE magnetometer data. These authors find two bands of waves with frequencies $f < \Omega_p$. '1'here is a higher frequency band $\Omega_{He^{++}} < f < \Omega_p$ and a band with $f < \Omega_{He^{++}}$. The higher frequency band is composed of transverse left-hand polarized waves while those waves with $f < \Omega_{He^{++}}$ arc linearl y polarized. These results coupled with an observed strong proton temperature anisotropy of $T_\perp/T_\parallel - 1 \simeq 1.7$ in the PDL, led Anderson et a]. to conclude that these emissions arc electromagnetic ion cyclotron wave.s and arc produced by the scenario proposed by Gary et al. (1992). Anderson et ai. also conclude that the waves observed by Song et a]. (1990) exhibited linear polarization and a single spectral peak centered near $\Omega_p/2$ ($\Omega_{He^{++}}$) and therefore "do not admit to the interpretation of generation by the ion cyclotron instability".

At Jupiter, in a region of the magnetosheath quite close to the magnetopause (which most probabl y corresponds to a Jovian 1)111,), we find waves with frequencies of - 0.2.5-0.45 Ω_p, assuming B_0 - 5 n']'. The frequencies arc only approximate, however. The field varies throughout the interval, altering the local gyrofrequency. Also because the waves arc detected in the magnetosheath where there arc convective motions, significant wave Doppler shifts arc possible. Thus a more careful analysis is warranted at a later date. It is also possible that a Ω_{He}^{++} notch is present in our data, as was found in the Anderson et al. (1991) results. What we find to be quite striking is that right-, left- and linearly polarized waves arc all detected within a single wave packet, If one assumes all of the cycles of a wave packet arc generated by the same instability, these results indicate that the Earth PDL wave observations of Song et al. (1990) and Anderson et al. (J991) may not be as disconnected as one might first assume. Propagation across the double ion (H, He^{++} in the magnetosheath) crossover frequency (3'home and Moses, 1983) may cause wave polarization reversals giving right- as well as left- hand polarized waves. The Anderson et al. Ω_{He}^{++} notch may be a double ion stop-band. Clearly, careful analysis is needed in this area. 1 lowever, this is beyond the scope of the present analysis and will be postponed until further more detailed work is possible.

Low Latitude Boundary Layer

Although broadband ELF/VLF and LF waves have been detected in the Earth's low latitude boundary layer (Gurnett et al., 1979; Perraut et al. 1979; Tsurutani et a]., 1981; 1982; 1989; Anderson et al., 1982; Gendrin, 1983; LaBelle and Treumann, 1988; Thorne and Tsurutani, 1991), this is the first time such enhanced noise has been discovered in a Jovian boundary layer. Wc have. found that enhanced electromagnetic waves exist at frequencies just below the proton cyclotron frequency, a feature similar to that found by Gendrin (1983) in the Earth's low latitude boundary layer. Since the Ulysses magnetometer frequency range does not extend to the ELF/VLF values, wc cannot comment on whether these emissions arc part of a broadband spectrum as exists at Earth or not. '1'here is an excellent plasma wave experiment onboard Ulysses (Stone et al., 1992) capable of these measurements, and wc arc presently collaborating with researchers on this team to look into this possibility.

The presence of waves at and near the Jovian magnetopause has important consequences for particle diffusion across this boundary. Resonant interactions with magnetosheath and/or magnetospheric ions with either electromagnetic and/or electrostatic waves can lead to significant crwss-field diffusion. Magnetosheath protons can diffuse into the magnetosphere, possibly forming the boundary layer, and magnetospheric ions can be diffused outward into the magnetosheath, allowing eventual escape into interplanetary space. A formal expression for the cross-field scattering rate have been derived in Tsurutani and Thorne (1982). in equation 3 below, wc give the expression for diffusion due to resonant interactions with the magnetic component of electromagnetic waves:

$$D_{\perp,B} \cong 2\,(B_w/B_o)^2\, D_{max}$$

where B_w is the. wave amplitude and D_{max} is the maximum, or Bohm diffusion rate. The latter is given by:

$$D_{max} = E_\perp c/2eB_o = 5 \times 10^5\, E(keV)/B_o(nT)\ km^2\ s^{-1} \qquad (4)$$

where $E_\perp$ is the. perpendicular kinetic energy of the particle in keV, and B_o the ambient magnetic field in nT. At the Jovian boundary layer the ambient magnetic field is 5 nT. Assuming a magnetosheath proton energy of 1 keV, D_{max} is 10^5 km^2 s^{-1}. The Bohm diffusion rate is one order of magnitude higher than that of the Earth because the field is weaker by approximately a factor of 10. Using the magnetic power of $B_w^2 \cong 10^{-1}$ nT^2, taken from Figure 9, wc get a value of 10^3 km^2 s^{-1} for $D_{\perp,B}$.

To get an estimate of the thickness of the Jovian boundary layer that could be generated by such a diffusion process, we use a lime scale. of the convection from the nose. of the. magnetopause to the flank. A sheath velocity of 100 kni s^{-1} and a distance of ~ 1 50 R_J are assumed. For 1 keV protons. the boundary layer thickness will be - 0.15 R_J.

The diffusion rate and boundary layer thickness will be much larger if the ions of concern are more energetic (see equation 4 and discussion in Gendrin, 1983). For 100 keV protons, d =- 1.4 R_J. It is also possible that if substantial electrostatic waves arc present (as at Earth), cross field diffusion can occur at an even more rapid rate (see discussion in Tsurutani and Thorne, 1982 and , Gendrin 1983). Wc will have to await further analyses of the ELF and LF electric wave data to see if this may be the case.

Magnetospheric Waves

Following the same arguments given for the upstream waves, we can calculate the resonant ion energies using the local Alfvén velocity. Bame et al. (1992) give a density value of 3 x 10-2 cm^{-3} at the time of wave occurrence. B_0 is - 8 I i']'. V_A is thus 1 x 10^3 km s^{-1}. The most likely resonant interaction is the loss cone instability in which magnetospheric ions and the generated waves arc propagating in opposite directions to each other:

$$\omega + k_{\|} V_{\|} = \Omega_i \tag{5}$$

At [his time, we do not have the ability to identify [he. ion species, but wc will take S^+ as a representative example. If wc usc the given numbers, we find that 60 keV S^+ ions will resonate with the given waves.

Acknowledgments. Portions of this paper work done at he Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract with National Aeronautics and Space Administration.

REFERENCES

Anderson, B. J., S. A. Fuselier and). Murr, Electromagnetic Ion Cyclotron Waves Observed in the Plasma)epletion ayer, Geophys. Res. Lett., 18, 1955, 1991.

Anderson, R. R., C. C. Harvey, M. M. Hoppe, B. T. Tsurutani, T. E. Eastman and J tcheto, Plasma Waves Near the Magnetopause, J. Geophys. Res., 87, 2087, 982.

Balogh, A., M. K.)ougherty, R. J. Forsyth,). J. Southwood, E. J. Smith, . T. Tsurutani, N. Murphy and M. E. Burton, Magnetic Field Observations During The Ulysses lyby of Jupiter, Science, 992a.

Balogh, A., T. J. Beck, R. J. Forsyth, P. C. Hedgecock, R. J. Marquedant, E. J. Smith, D. J. Southwood and B. T. Tsurutani, The Magnetic ield Investigation on the Ulysses Mission: Instrumentation and Preliminary Scientific Results, Astron. and Atrophys. Suppl. Ser. 92, 221, 992b.

Bame, S. J., B. . Barraclough, W. D. Feldman, G. R. Gisler, J. T. Gosling, D. J. McComas, J. I Phillips and M. F. Thomsen, Jupiter's Magnetosphere: Plasma Description from the Ulysses Flyby, Science, 992a.

Bame, S. J., D. J. McComas, B. . Barraclough, J. Phillips, K. J. Sofaly, J. C. Chavez, B. E. Goldstein and R. K. Sakurai, The Ulysses Solar Wind Plasma xperiment, Astron. and Astrophys. Suppl. Ser., 92, 237, 992b.

Brinca, A. ., N. Sekopke and G. Paschmann, Wave Excitation Downstream of the Low-β Quasi Perpendicular Bow Shock, J. Geophys. Res., 95, 633 990.

Bame, S. J., B. L. Barraclough, W. D. Feldman, G. R. Gisler, J. '1'. Gosling, D. J. McComas, J. L. Phillips and M. F. Thomsen, Jupiter's Magnetosphere: Plasma Description from the Ulysses Flyby, Science, 1992a.

Bame, S. J., D. J. McComas, B. L. Barraclough, J. L. Phillips, K. J. Sofaly, J. C. Chavez, B. E. Goldstein and R. K. Sakurai, The Ulysses Solar Wind Plasma Experiment, Astron. and Astrophys. Suppl. Ser., 22,237, 1992b.

Brinca, A. L., N. Sckopke and G. Paschmann, Wave Excitation Downstream of the Low-β Quasi Perpendicular Bow Shock, J. Geophys. Res., 95, 6331, 1990.

Chandrasekhar, S. A., A. N. Kaufmann, and K. M. Watson, The Stability of the Pinch, Proc. Royal Soc. London Ser. A., 24.5.,435, 1958.

Croley, D. R., Jr., J. F. Fennell and B. G. Ledley, Observation of Reconnection Phenomena at Synchronous orbit, J. Geophys. Res., 91,4321, 1986.

Fairfield, D. H. and K. W. Behannon, Bow Shock and Magnetosheath Waves at Mercury, J. Geophys. Res., 81, 3897, 1976.

Gary, S. P., Electromagnetic ion/Ion instabilities and '1'heir Consequences in Space Plasmas: A Review, Space Science Rev, 56,373, 1991.

Gary, S. P., The Mirror and Ion Cyclotron Anisotropy Instabilities, J. Geophys. Res., 97, 8519, 1992a.

Gary, S. P., S. A. Fuselier and B. J. Anderson, Ion Anisotropy instabilities in the Magnetosheath, J. Geophys. Res., in press 1992b.

Gendrin, R., Magnetic Turbulence and Diffusion Processes in the Magnetopause Boundary Layer, Geophys. Res. Lett., 10,769, 1983.

Gleaves, D. G. and D. J. Southwood, Phase Delays in Transverse Disturbances in the Earth's Magnetosheath, Geophys. Res. Lett., 17, 2249, 1990.

Gleaves, D. G. and D. J. Southwood, Magnetohydrodynamic Fluctuations in the Earth's Magnetosheath at 1500 LT; ISEE-1 and ISEE-2, J. Geophys. Res., 96, 129, 1991.

Goldstein, **M. 1,., C. W.** Smith **and W. 11.** Mattaeus, large Amplitude MHD Waves Upstream of the Jovian Bow Shock, J. Geophys. Res., 88,9989, 1983.

Goldstein, M. I.., H. K, Wong, A. F. Vinas and C. W. Smith, Large-Amplitude MHD Waves Upstream of the Jovian Bow Shock: Reinterpretation, J. Geophys. Res., 90, 302, 1985.

Goldstein, M. L., H. K. Wong and A. Eviatar, Excitation of MHD Waves Upstream of Jupiter by Energetic Sulphur or Oxygen ions, J. Geophys. Res., 91, 7954, 1986.

Glassmeier, K. 11., N. F. Ness, M. 11. Acuna and F. M. Neubauer, Studying Hydromagnetic Waves in the Io Plasma Torus: Voyager 1 Observations, J. Geophys. Res., 94, 15063, 1989.

Gurnett, D. A., R. R. Anderson, B. '1'. Tsurutani, E. J. Smith, G. Pashmann, G. Haerendel, S. J. Bame, and C. T. Russell, Plasma Wave Instabilities at the. Magnetopause: Observations from ISEE-1 and -2, J. Geophys. Res., 84, 7043, 1 979.

Hasagawa, A., Drift Mirror Instability in the Magnetosphere, Phys. Fluids, 12, 2642, 1969.

Hasagawa, A., Plasma Instabilities and Nonlinear Effects, Phys. and Chem. in Space 8, 94, Springer Verlag, New York, 1975.

Hoppe, M. hi., C. T. Russell, L. A. Frank, '1'. E. Eastman and E. W. Greenstadt, Upstream Hydromagnetic Waves and Their Association with Backstreaming lon Populations: ISEE 1 and 2 Observations, J. Geophys. Res., 86, 4471, 1981.

Hubert, D., C. C. Harvey and C. "I". Russell, Observations of Magnetohydro dynamic Modes in the Earth's Magnetosheath at 0600 LT, J. Geophys. Res., 94, 17305, 1989.

Lee, L. C., C. P. Price, C. S. Wu and M. E. Mandt, A Study of Mirror Waves Generated Downstream of a Quasi-Perpendicular Shock, J. Geophys. Res., 93, 247, 1988.

Lepping, R. P., A. J. Lazarus, 1,. J. Moriarity, P. Milligan, R. S. Kennon, R. E. McGuire and W. 11. Mish, IMP-8 Solar Wind Magnetic Field and Plasma Data in Support of LJlysscs-Jupiter Encounter: 13-31, January 1992, NASA GSFC document, 1993.

Migliuolo, S., The Field Swelling and Mirror Modes: Connection of the Two Instabilities, J. G.CW!-YA.!3!2s.,9J.,7981 , i 986.

Omidi, N. and D. Winske, Steepening of Kinetic Magnetosonic Waves into Shocklets: Simulations and Consequences for Planetary Shocks and Comets, L Geophys. Res., $25,2281, 1990.

Patel, V. L., P. H. Ng, L. J. Cahill, Jr., Drift Wave Model for Geomagnetic Pulsations in a High β Plasma, J. Geophys. Res., 88, 5677, 1983.

Perraut, S., R. Gendrin, P. Robert, and A. Roux, Magnetic Pulsations Observed Onboard Gl\OS-2 in the ULF Range during Multiple Magnetopause Crossings, in Proc. Mag. Boundary Layer Conf., Alpbach, ESA/SP-148, 11 31979.

Price, C. P., D. W. Swift and L. C. Lee, Numerical Simulations of Nonoscillatory Mirror Waves at the Earth's Magnetosheath, J. Geophys. Res., 91, 101, 1986.

Price, C. P., Mirror Waves Driven by Newborn Ion Distributions, J. Geophys. Res., 94, 15001, 1989.

Russell, C. T., W. Riedler, K. Schwingenschuh, and Y., Yeroshenko, Mirror instability in the Magnetosphere of Comet Halley, Geophys. Res., Lett., 14, 644, 1987.

Sckopke, N., G. Paschmann, A. L. Brinca, C. W. Carlson, and J. H. Lühr, Ion Thermalization in Quasi-perpendicular Shocks Involving Reflected Ions, J. Geophys. Res., 95, 6337, 1990.

Smith, C. W., M. L. Goldstein and W. H. Mathaeus, Turbulence Analysis of the Jovian Upstream "Wave" Phenomenon, J. Geophys. Res., 1.8..>5581, 1983.

Smith, C. W., M. L. Goldstein, and W. H. Matthaeus, "Correction to Turbulence Analysis of the Jovian Upstream "Wave" Phenomenon," J. Geophys. Res., 89, 9 1 59, 1984.

Smith, C. W. and M. A. Lee, Coupled Hydromagnetic Wave Excitation and Ion Acceleration Upstream of the Jovian Bow Shock, J. Geophys. Res., 91, 81, 1986.

Smith, E. J. and B. T. Tsurutani, Magnetosheath Lion Roars, J. Geophys. Res., 81, 2261, 1976.

Smith, E. J. and J. H. Wolfe, Observations of Interaction Regions and Corotating Shocks between One and Five AU: Pioneer 10 and 11, Geophys. Res. Lett., 3, 137, 1976.

Smith, E. J. and B. T. Tsurutani, Saturn's Magnetosphere: observations of Ion Cyclotron Waves Near the Dione L Shell, J. Geophys. Res., 88, 7831, 1983.

Smith, E. J., B. T. Tsurutani, J. A. Slavin, E. L. Scarf and S. J. Bame, Waves in the Giacobini-Zinner Magnetosheath: ICE Observations in Proc. Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets, ed. H. Oya and B. T. Tsurutani, Sohbun Insatsu, Sendai, Japan, 18, 1987.

Smith, E. J., K. P. Wenzel and D. E. Page, Ulysses at Jupiter: An Overview, Science 257 1503, 1992.

Song, P., R. C. Elphic, C. T. Russell, J. T. Gosling and C. A. Cattell, Structure and Properties of the Subsolar Magnetopause for Northward IMF: ISEE Observations, J. Geophys. Res., 95, 6375, 1990.

Southwood, D. J. and M. G. Kivelson, Mirror Instability 1: The Physical Mechanism of Linear Instability, J. Geophys. Res., in press, 1993.

Thorne, R. M. and B. T. Tsurutani, The Generation Mechanism for Magnetosheath Lion Roars, Nature, 293, 384, 1981.

Thorne, R. M. and J. Moses, Electromagnetic Ion-Cyclotron instability in the Multi-Ion Jovian Magnetosphere, Geophys. Res. Lett., 10, 631, 1983.

Thorne, R. M. and B. T. Tsurutani, Resonant Interactions between Cometary Ions and Low Frequency Electromagnetic Waves, Planet. Space Sci. 35, 1501, 1987.

Thorne, R. M. and B. T. Tsurutani, Wave-particle interactions in the Magnetopause Boundary Layer, in Phys. of Space Plasmas (1990), ed. by T. Chang, G. B. Crew and J. R. Jasperse, Scientific Publ. Inc., 119, 1991.

Tsurutani, B. T. and P. Rodriguez, Upstream Waves and Particles: An Overview of ISEE Results, J. Geophys. Res., 86, 4319, 1981.

Tsurutani, B. T., E. J. Smith, R. M. Thorne, R. R. Anderson, D. A. Gurnett, G. K. Parks, C. S. Lin and C. T. Russell, Wave-particle Interactions at the Magnetopause: Contributions to the Dayside Aurora, Geophys. Res. Lett., 8, 183, 1981.

Tsurutani, B. T., E. J. Smith, R. R. Anderson, K. W. Ogilvie, J. D. Scudder, D. J. Baker, and S. J. Bame, Lion Roars and Nonoscillatory Drift Mirror Waves in the Magnetosheath, J. Geophys. Res., 87, 6060, 1982.

Tsurutani, B. T. and R. M, Thorne, Diffusion Processes in the Magnetopause Boundary Layer, Geophys. Res. Lett., 9, 1247, 1982.

Tsurutani, B. "1'., I. G. Richardson, R. P. Lepping, R. D. Zwickl, D. E. Jones, E. J. Smith and S. J. Bame, Drift Mirror Mode Waves in the Distant ($X \cong 200$ R_e) Magnetosheath, Geophys. Res. Lett., 11$1102>1984.

Tsurutani, B. T., R. M. Thorne, E. J. Smith, J. 'I'. Gosling and 11. Matsumoto, Steepened Magnetosonic Waves at Comet Giacobini-Zinner, J. Geophys. Res., 92, 11074, 1987a.

Tsurutani, B. T., A. L. Brinca, E. J. Smith, R. M. Thorne, F. L. Scarf, J. 'I'. Gosling, and F. M. Ipavich, MHD Waves Detected by ICE at Distances $\geq 28 \times 10^6$ km from Comet P/Halley: Cometary and Solar Wind Origin?, Astron. Astrophys., 187, 97, 1987b.

Tsurutani, B., A. L. Brinca, E. J. Smith, R. 'J'. Okida, R. R. Anderson and T.11. Eastman, A Statistical Study of ELF-VLF Plasma Waves at the Magnetopause, J. Geophys. Res., 94, 1270, 1989.

Tsurutani, B. 'I'., Comets: A Laboratory for Plasma Waves and Instabilities, in Cometary Plasma Processes, cd. by A. Johnstone, Am. Geophys. Un. Press, 61, 189, 199].

Tsurutani, B. T., Nonlinear Low Frequency (LF) Waves: Comets and Foreshock Phenomena, Phys. of Space Plasmas (1991), cd. by "1'. Chang et al., Sci Publ. Inc., Cambridge, MA, 11, 91, 1992.

Tsurutani, B. "1'., D. J. Southwood, E. 1. Smith and A. Balogh, Nonlinear Magnetosonic Waves and Mirror Mode Structures in the March 1991 Ulysses Interplanetary Event, Geophys. Res. Lett., 19, 1267, 1992..

Yeroshenko, Y. G., V. A. Styashin, W. Riedler, K. Schwingenschuh, and C. '1'. Russell, Fine Structure of the Magnetic Field on Cometary P/Halley's Comet, Astron. Astrophys. 187, 69, 1987.

Zwan, B. J. and R. A. Wolf, Depletion of the Solar Wind Plasma Near a Planetary Boundary, J. Geophys. Res., 81, 1636, 1976.

FIGURE CAPTIONS

Figure 1. The Ulysses Trajectory in the Jupiter orbital plane. Adapted from Smith et al., 1992.

Figure 2. An example of foreshock 10^{-2} Hz waves detected on the inbound pass. The inset shows a large amplitude high frequency (25s) whistler wave packet.

Figure 3. Hodograms of two parts of a steepened magnetosonic wave at ~ 1705 UT. The trailing portion of the wave (left-panel) is linearly polarized. The front part of the wave (right-panel) is left-hand circularly polarized in the spacecraft frame.

Figure 4. An example of 2 x 10^{-1} Hz waves. These high frequency oscillations are superposed on top of the 10-* Hz waves and typically occur near local |B| maxima.

Figure 5. Examples of Jovian magnetosheath mirror mode structures.

Figure 6. Mirror mode structures in high time resolution. The peak-to-minimum field values vary from 3-to- 1 to 4-10-1. θ_{kB} varies from 80° to 90° and the spacings between field magnitude decreases is ~ 10-20 r_p, assuming 1 keV magnetosheath protons.

Figure 7. Small amplitude waves detected in the Jovian magnetosheath, close to the magnetopause. The polarization of these waves are found to be highly variable.

Figure 8. A hodogram for a wave in Figure 7 from 1859:10 to 1859:51 UT. The wave is left-hand circularly polarized in the spacecraft frame, propagating at 33° relative to $\vec{B}_0$.

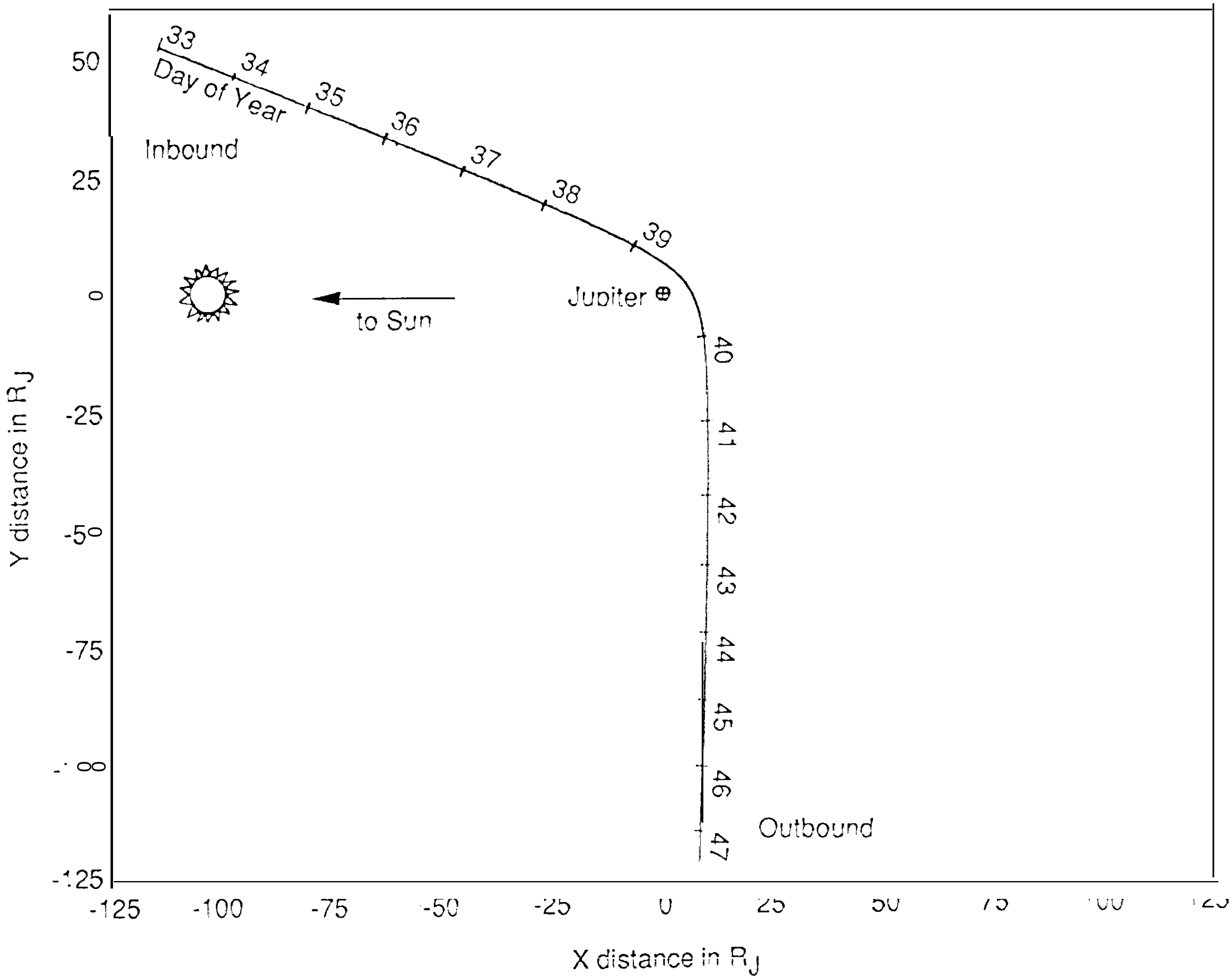
Figure 9. Wave power spectra within the magnetopause boundary layer. The spectra are for the three components of the field and magnitude in a field-aligned coordinate system .

Figure. 10. Magnetospheric waves with 5-8 min periods. The small amplitude waves are determined to be left-hand elliptically to circularly polarized propagating from 10° to 43° relative to $\vec{B}_0$.

Figure 11. A hodogram for the wave occurring between 1445:51 to 1457:10 UT. θ_{KB} is 25<' for this case. The wave is not plane polarized.

Figure 12. A schematic giving the orientation of magnetosheath fields and the. shock-generated plasma anisotropics for interplanetary magnetic fields a) perpendicular and b) parallel to the solar wind flow direction.

ULYSSES TRAJECTORY IN JUPITER ORBITAL PLANE



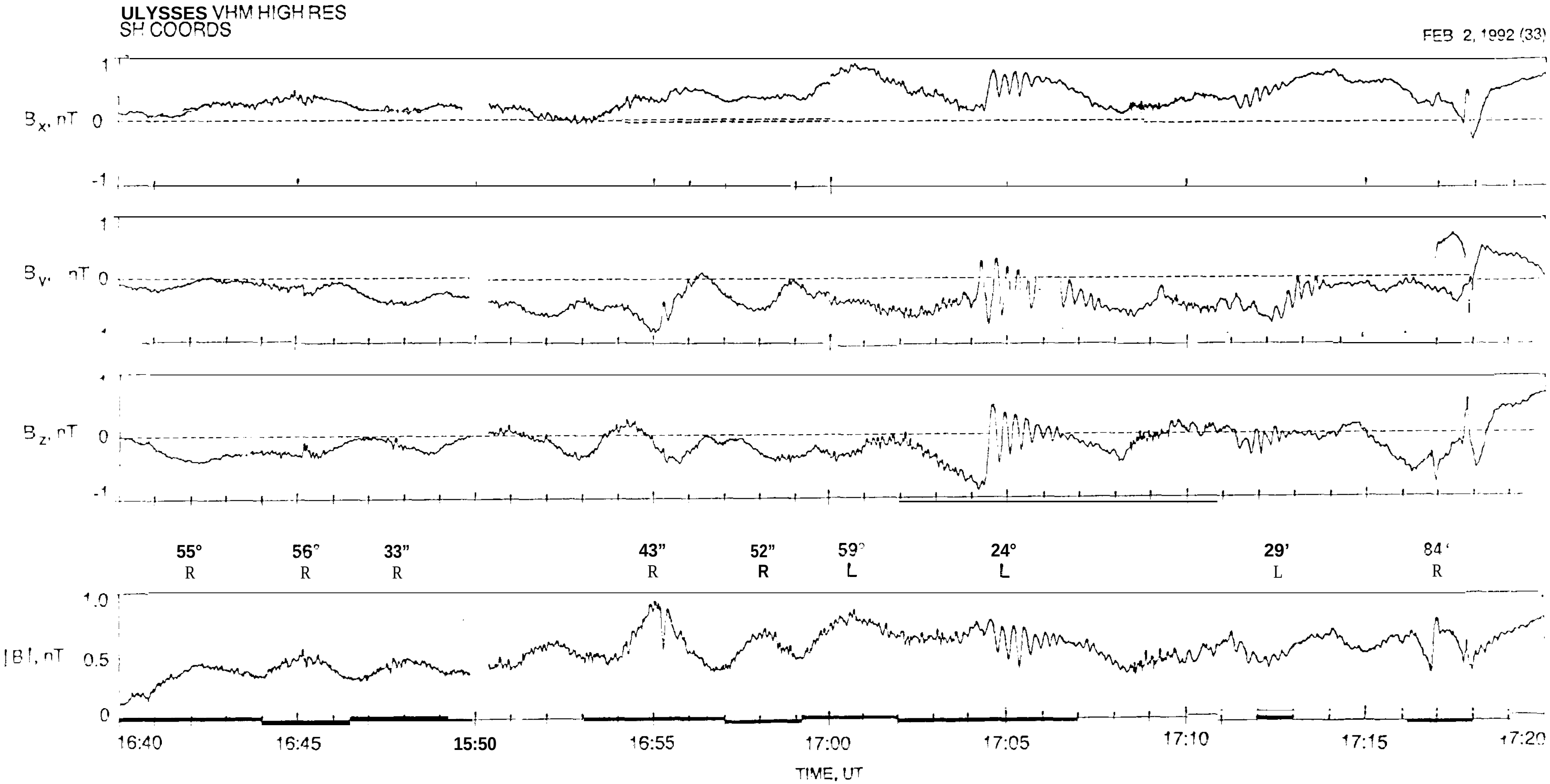

ULYSSES VHM HIGH RES
SH COORDS
FEB 2, 1992 (33)
Bx, nT
By, nT
Bz, nT
|B|, nT
55° R
56° R
33" R
43" R
52" R
59° L
24° L
29' L
84' R
16:40
16:45
15:50
16:55
17:00
17:05
17:10
17:15
17:20
TIME, UT

Fig. 2

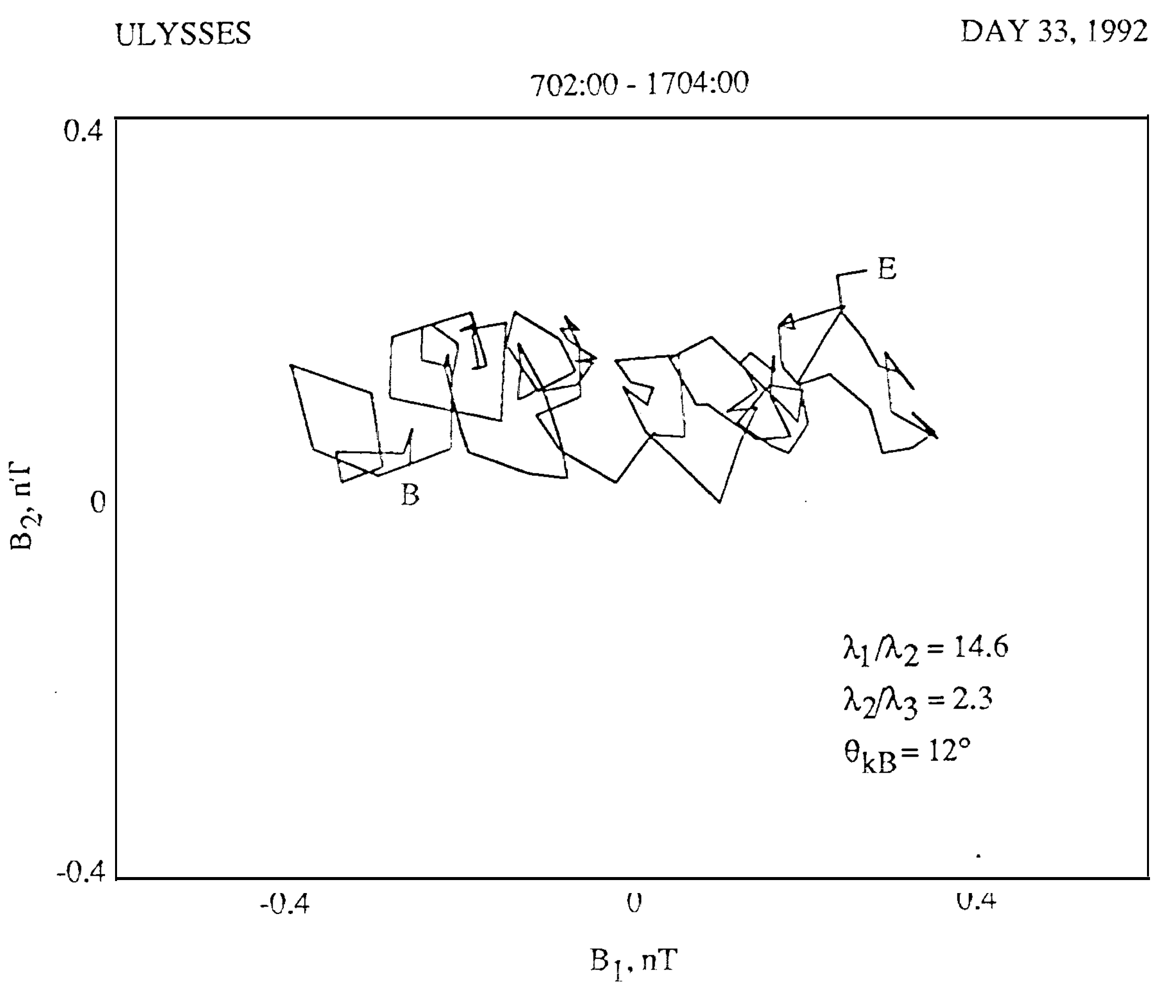

ULYSSES
DAY 33, 1992
702:00 - 1704:00
0.4
0
-0.4
B
E
$\lambda_1/\lambda_2 = 14.6$
$\lambda_2/\lambda_3 = 2.3$
$\theta_{kB} = 12°$
-0.4
0
0.4
B_1, nT
B_2, nT

Fig. 3a

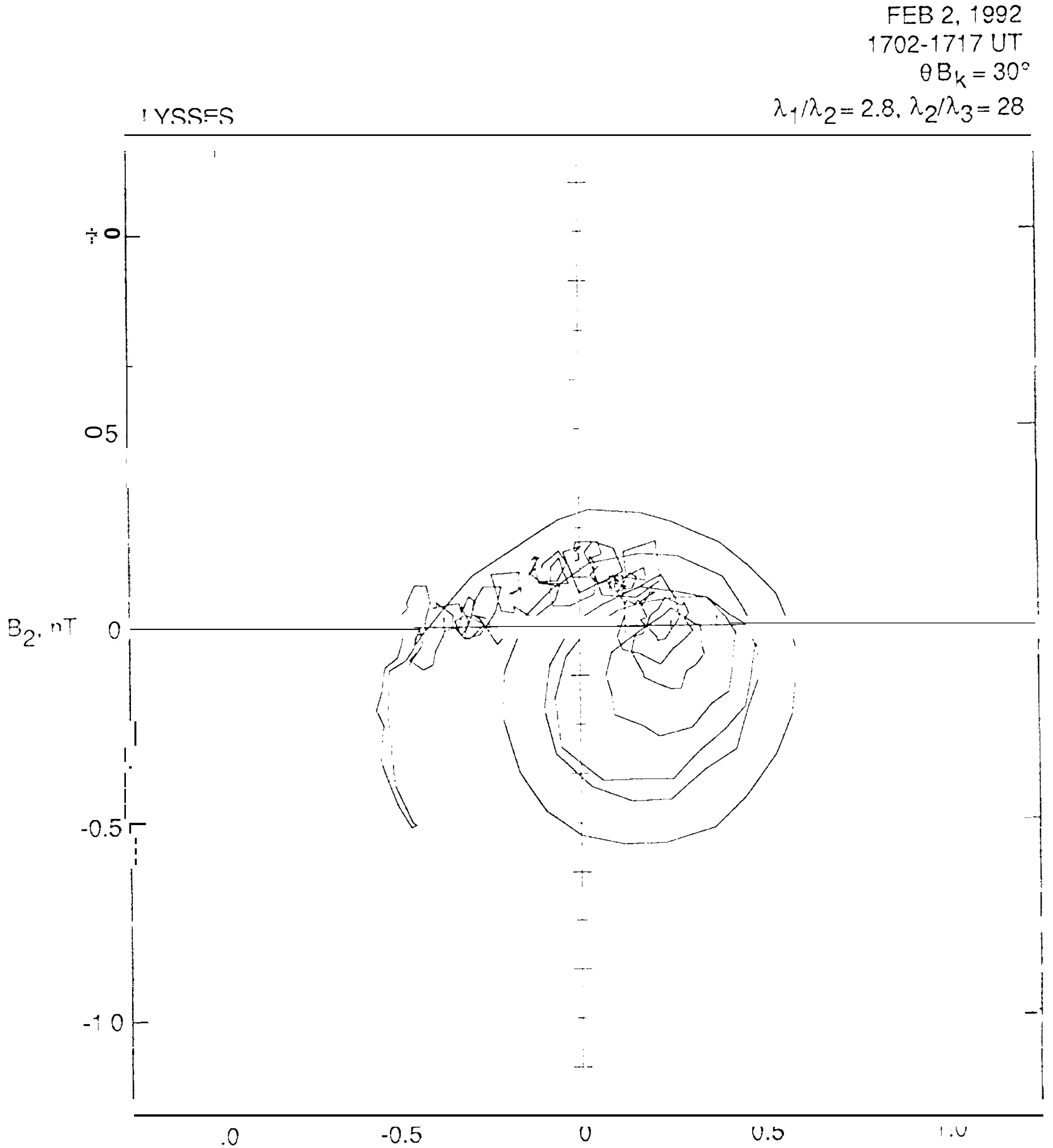
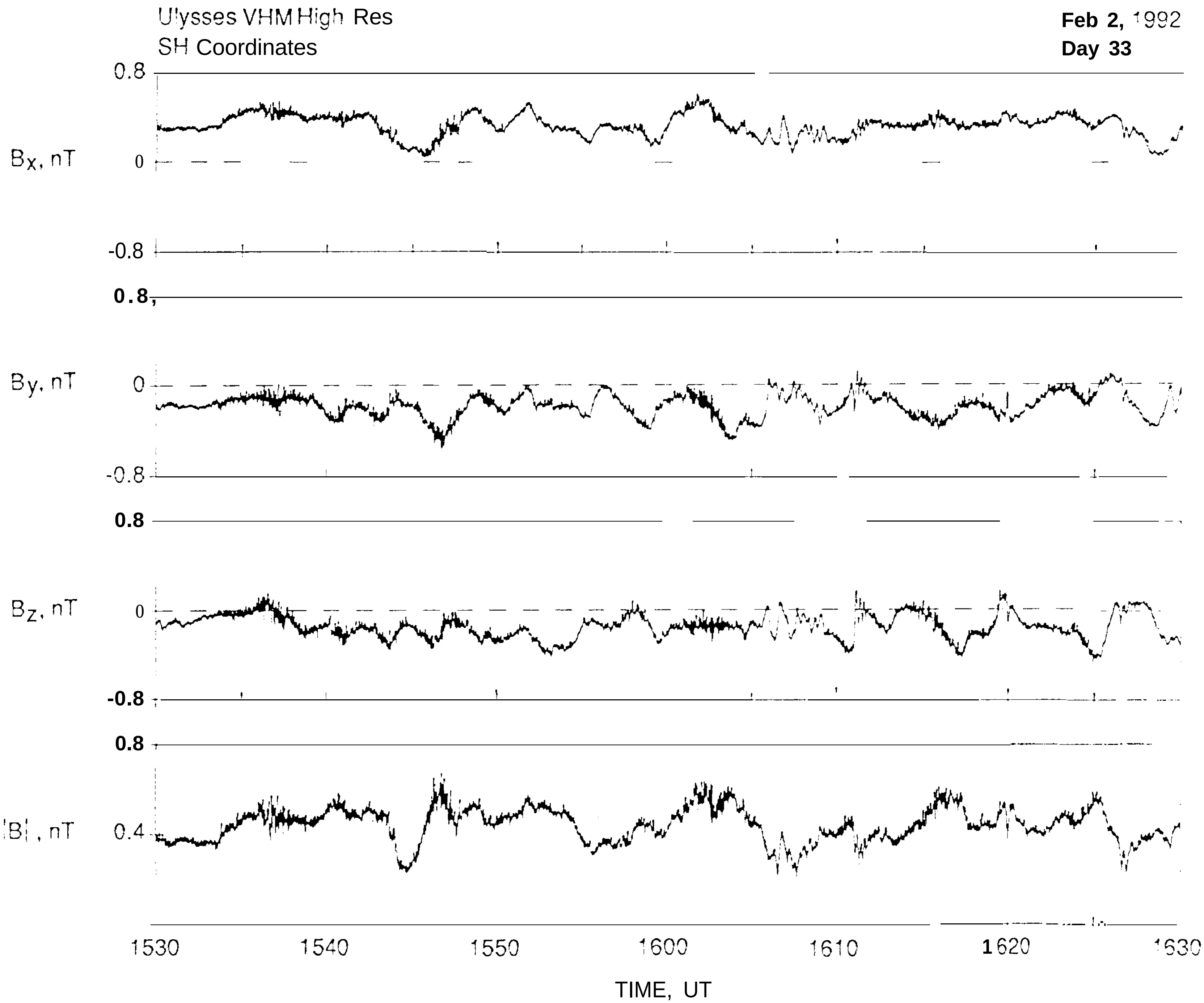
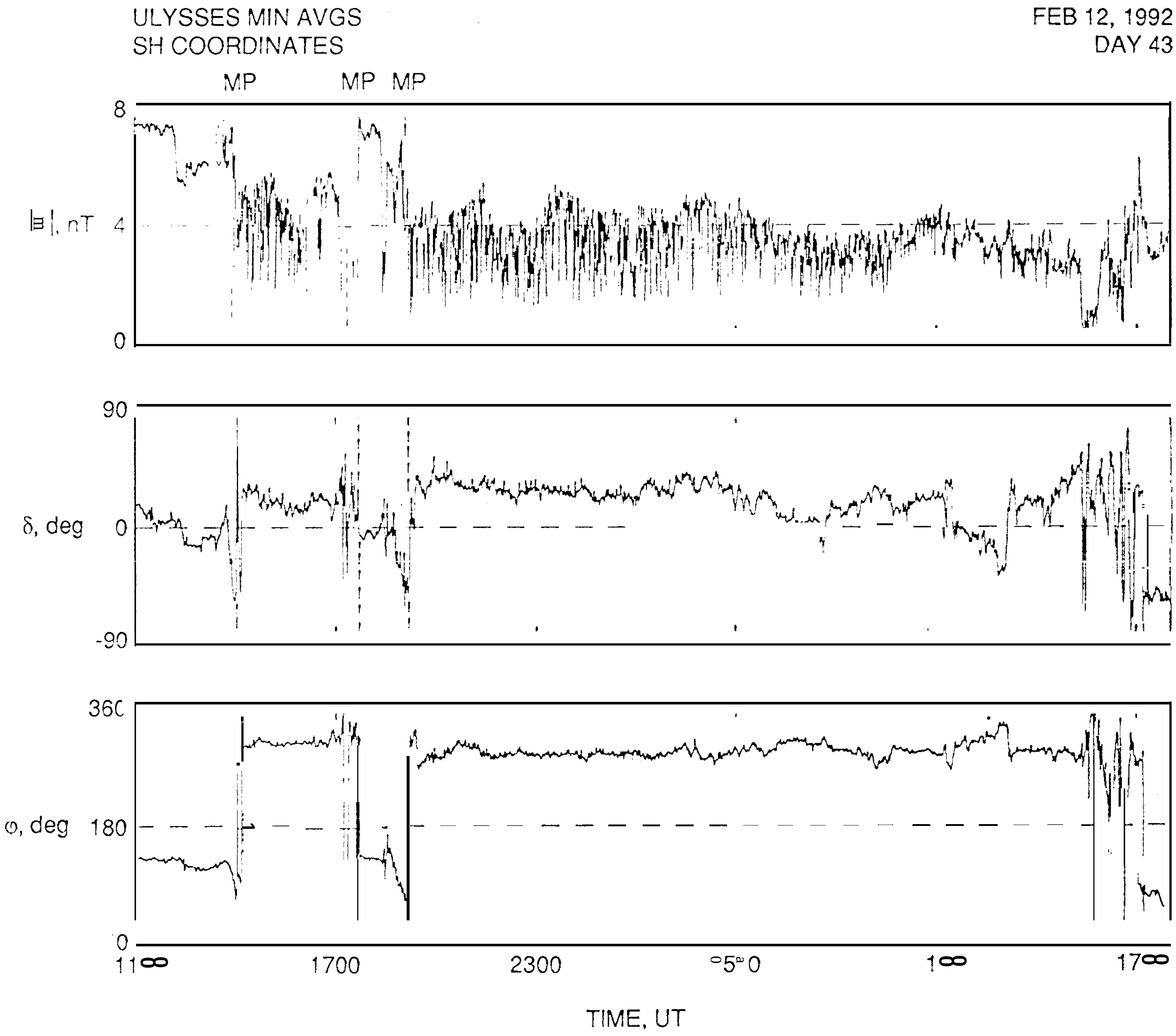

FEB 2, 1992
1702-1717 UT
$\theta B_k = 30°$
$\lambda_1/\lambda_2 = 2.8,\ \lambda_2/\lambda_3 = 28$
ULYSSES
B_2, nT
0
0.5
0
-0.5
-1.0
-0.5
0
0.5
1.0

Fig. 8b

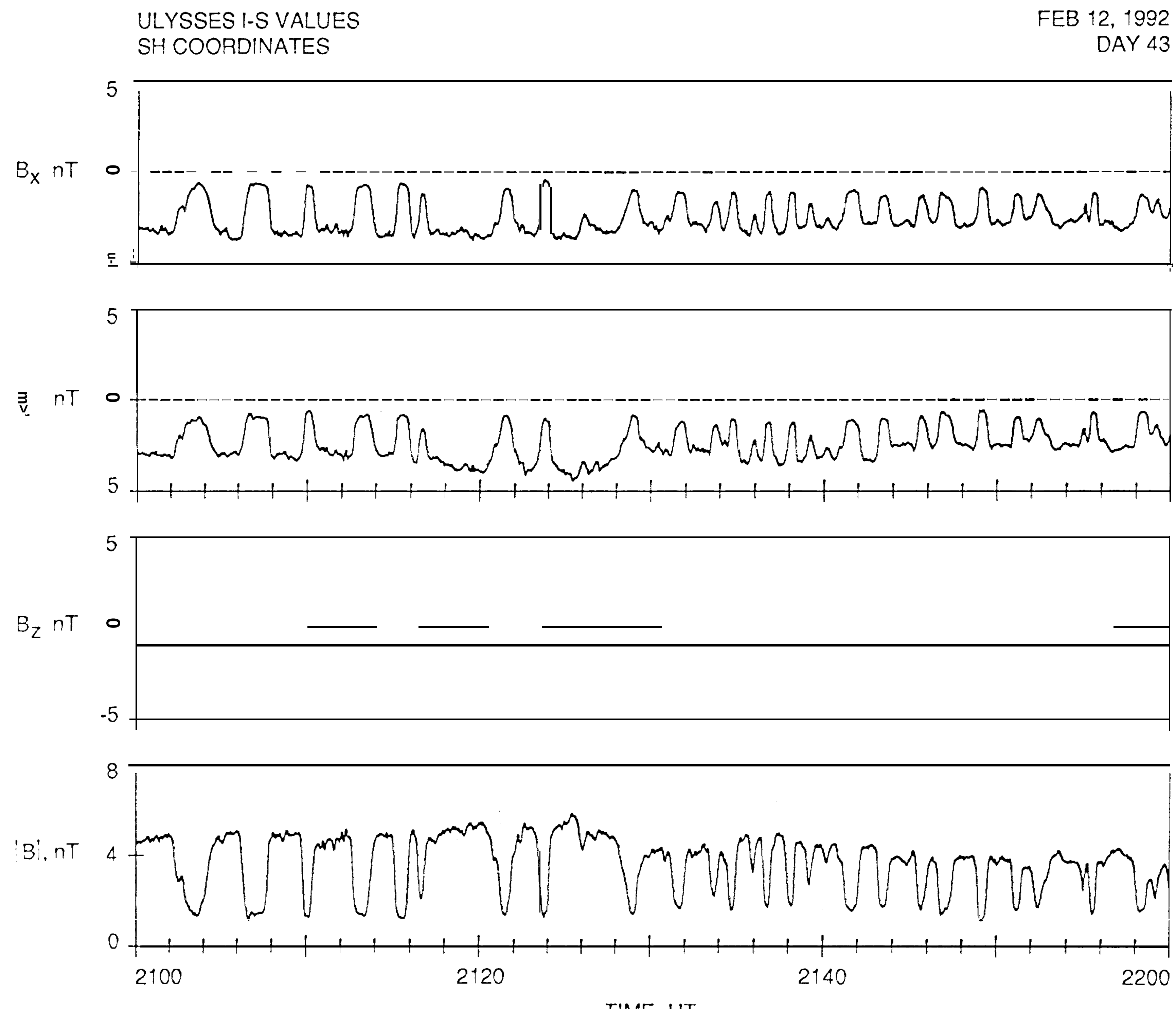


Ulysses VHM High Res
SH Coordinates
Feb 2, 1992
Day 33
Bx, nT
By, nT
Bz, nT
|B|, nT
0.8
0
-0.8
0.4
1530
1540
1550
1600
1610
1620
1630
TIME, UT



ULYSSES MIN AVGS
SH COORDINATES
FEB 12, 1992
DAY 43
MP
MP
MP
|B|, nT
8
4
0
δ, deg
90
0
-90
φ, deg
360
180
0
1100
1700
2300
0500
1100
1700
TIME, UT

Fig. 5



ULYSSES I-S VALUES
SH COORDINATES
FEB 12, 1992
DAY 43
B_X nT
B_Z nT
|B|, nT
5
0
-5
8
4
2100
2120
2140
2200

Fig. 6

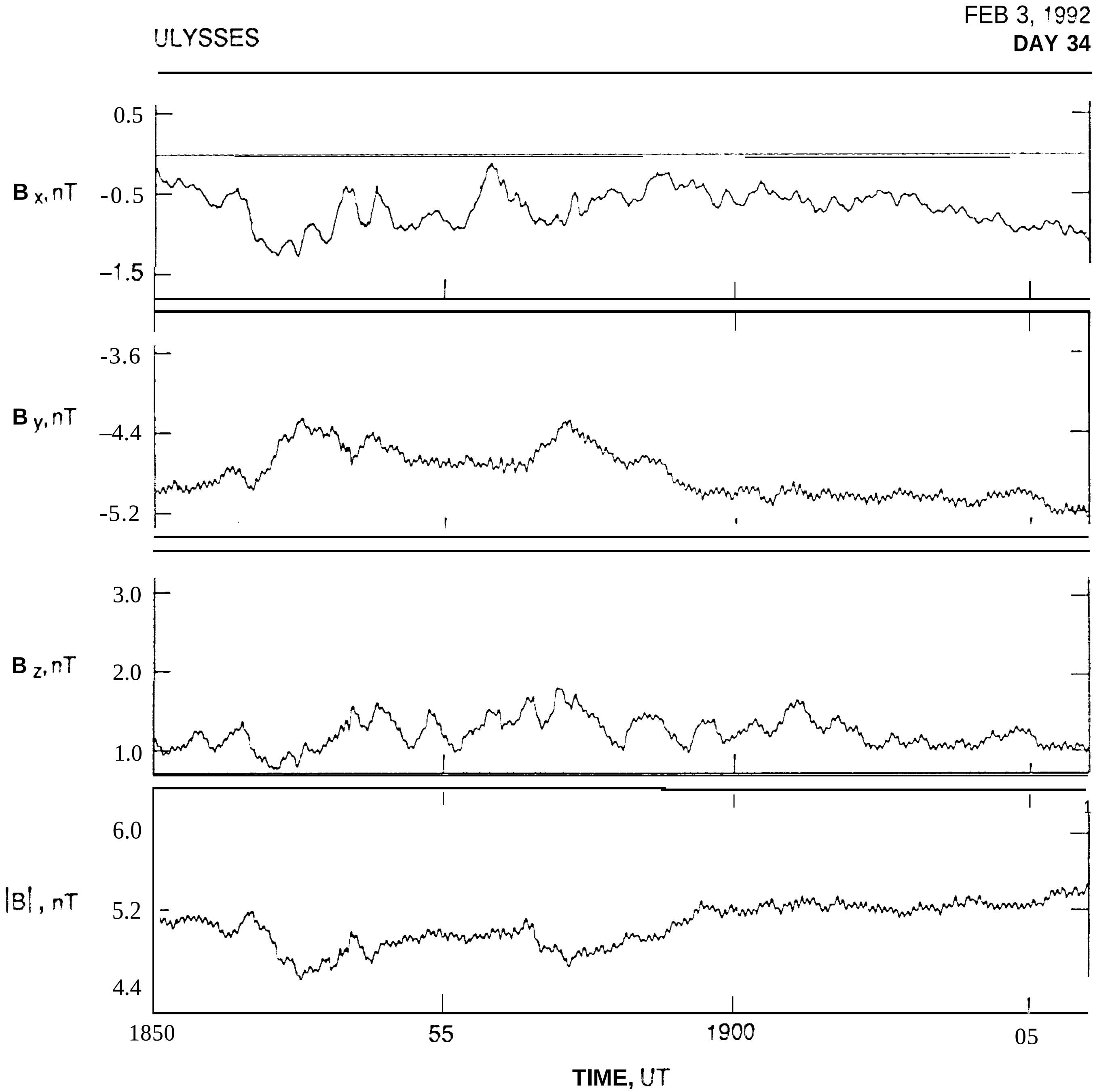

ULYSSES
FEB 3, 1992
DAY 34
0.5
-0.5
−1.5
B_x, nT
-3.6
−4.4
-5.2
B_y, nT
3.0
2.0
1.0
B_z, nT
6.0
5.2
4.4
|B|, nT
1850
55
1900
05
TIME, UT

Fig. 7

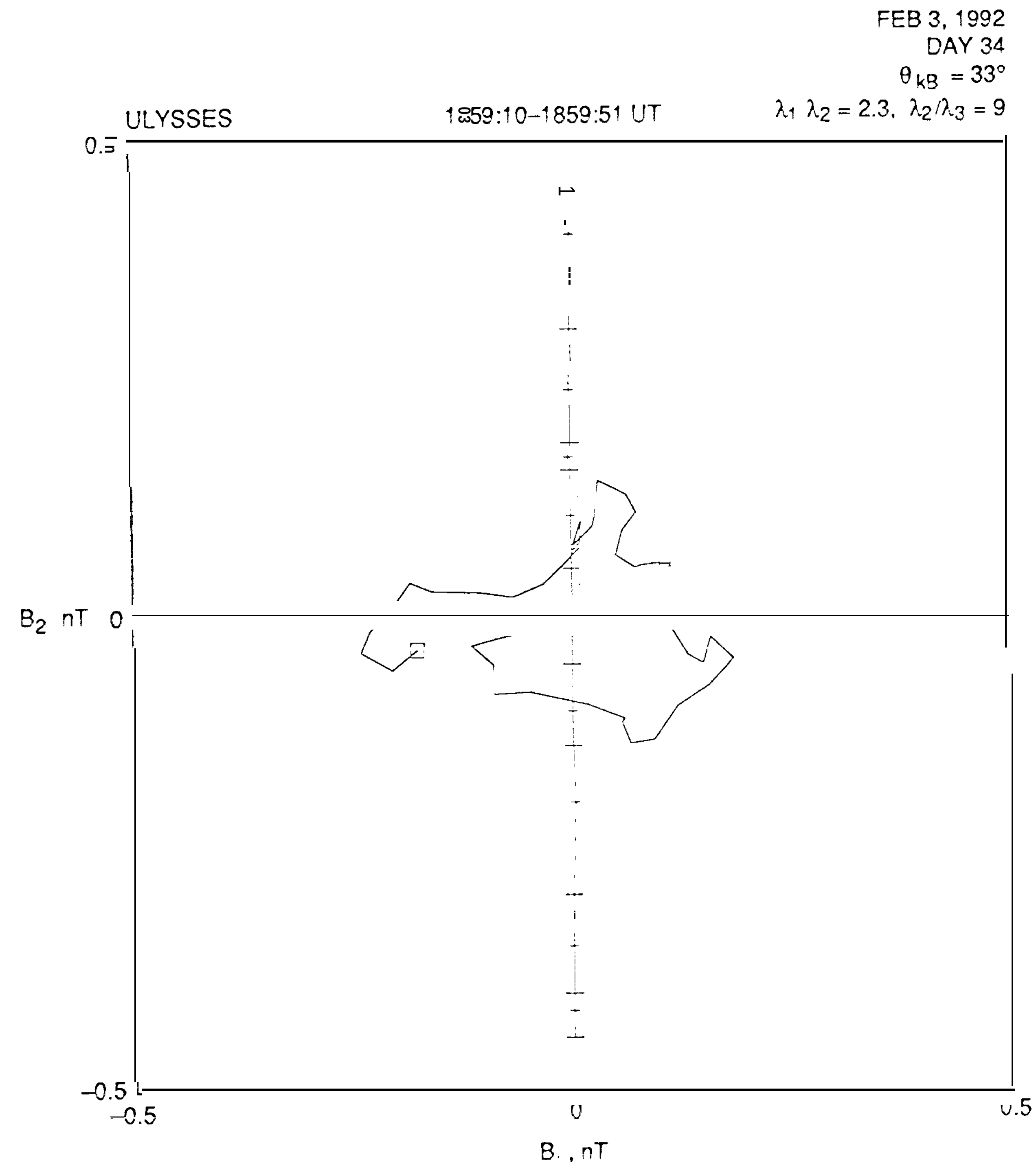

FEB 3, 1992
DAY 34
$\theta_{kB} = 33°$
$\lambda_1 \lambda_2 = 2.3,\ \lambda_2/\lambda_3 = 9$
ULYSSES
1859:10–1859:51 UT
0.5
B_2 nT 0
–0.5
–0.5
0
0.5
B , nT
1

Fig. 8

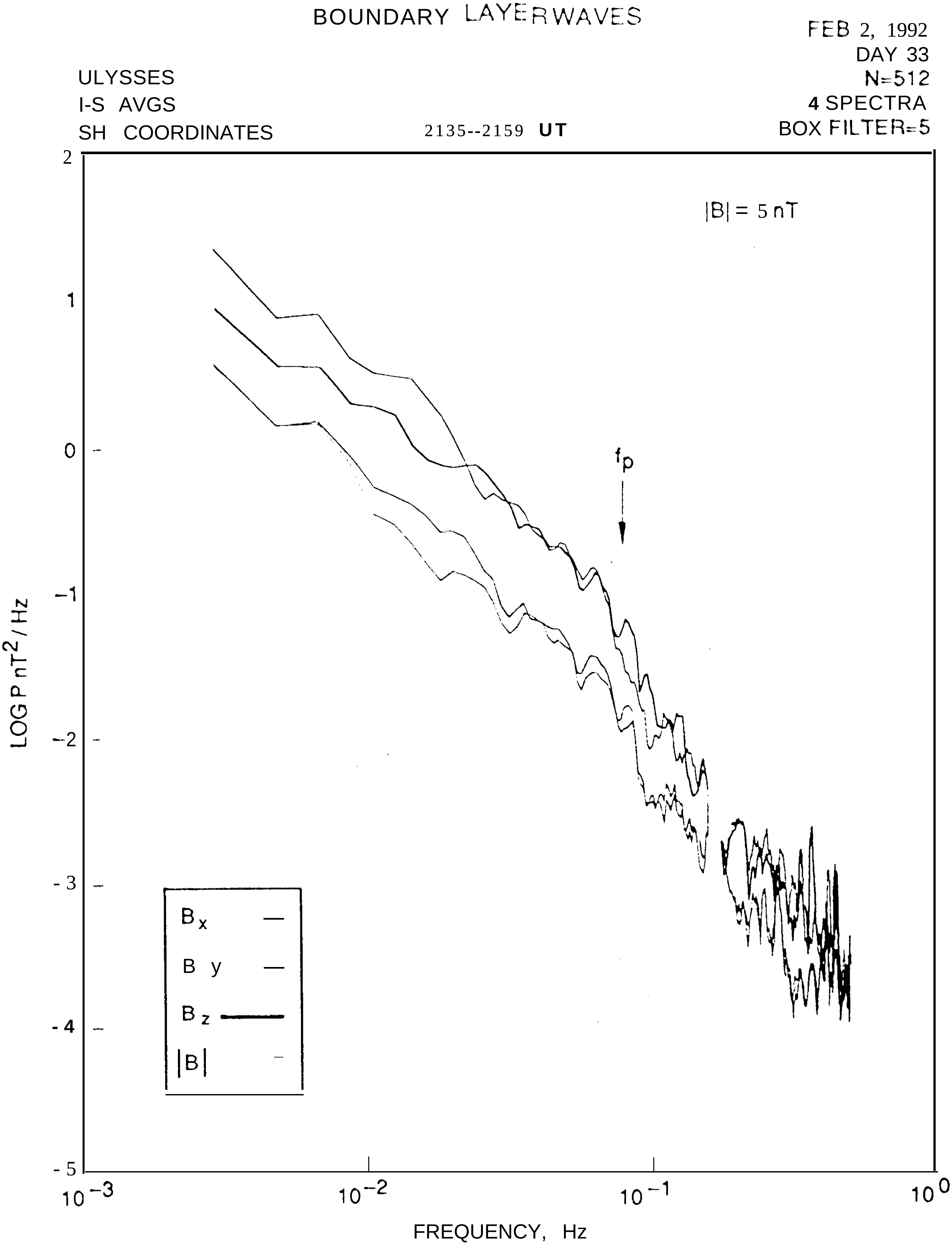

BOUNDARY LAYER WAVES
FEB 2, 1992
DAY 33
N=512
4 SPECTRA
BOX FILTER=5
ULYSSES
I-S AVGS
SH COORDINATES
2135--2159 UT
|B| = 5 nT
f_p
B_x
B_y
B_z
|B|
LOG P nT^2/Hz
2
1
0
−1
−2
-3
-4
-5
10^{-3}
10^{-2}
10^{-1}
10^{0}
FREQUENCY, Hz

Fig. 9

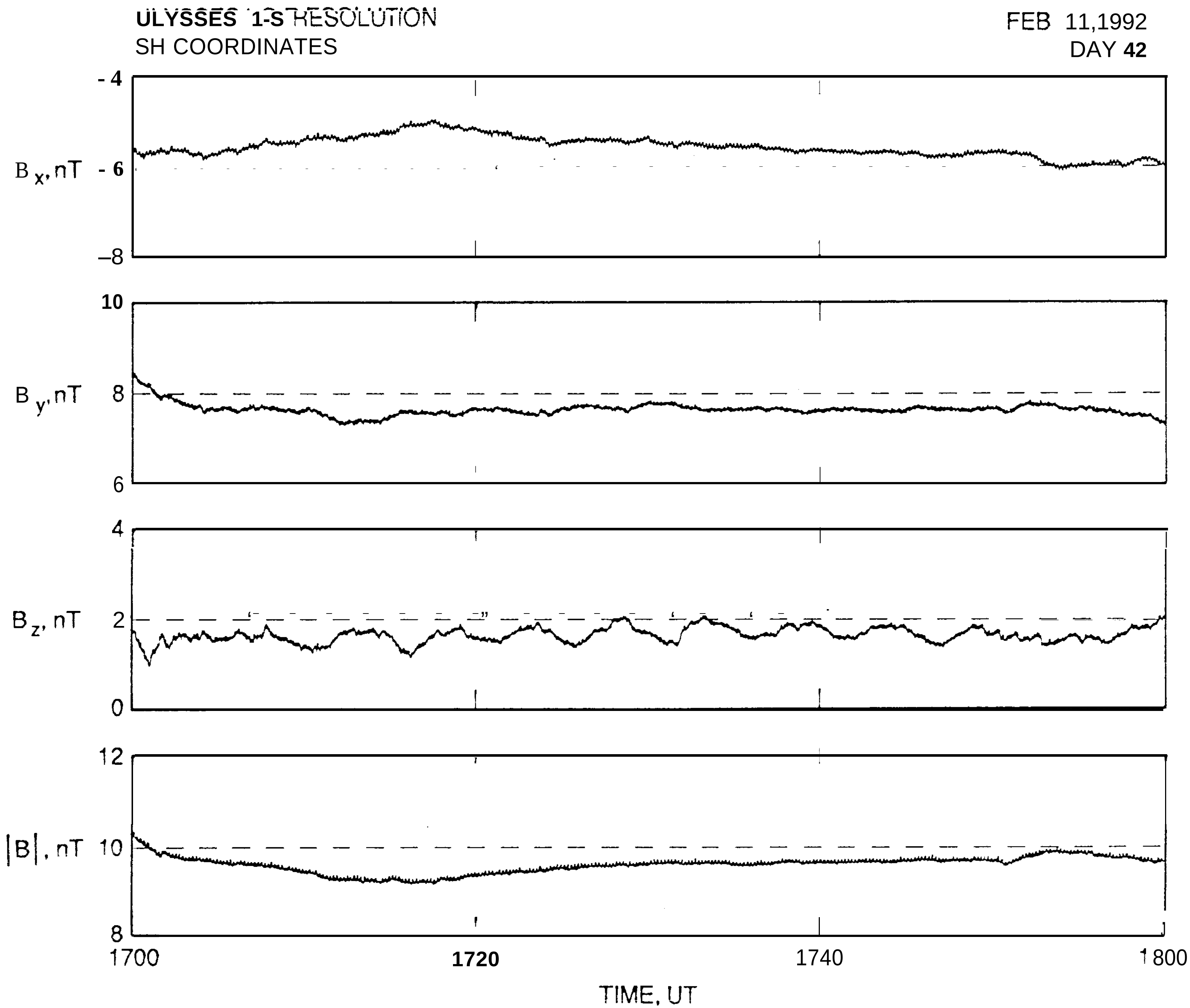

ULYSSES 1-S RESOLUTION
SH COORDINATES
FEB 11,1992
DAY 42
B_x, nT
B_y, nT
B_z, nT
|B|, nT
-4
-6
-8
10
8
6
4
2
0
12
10
8
1700
1720
1740
1800
TIME, UT

Fig. 10

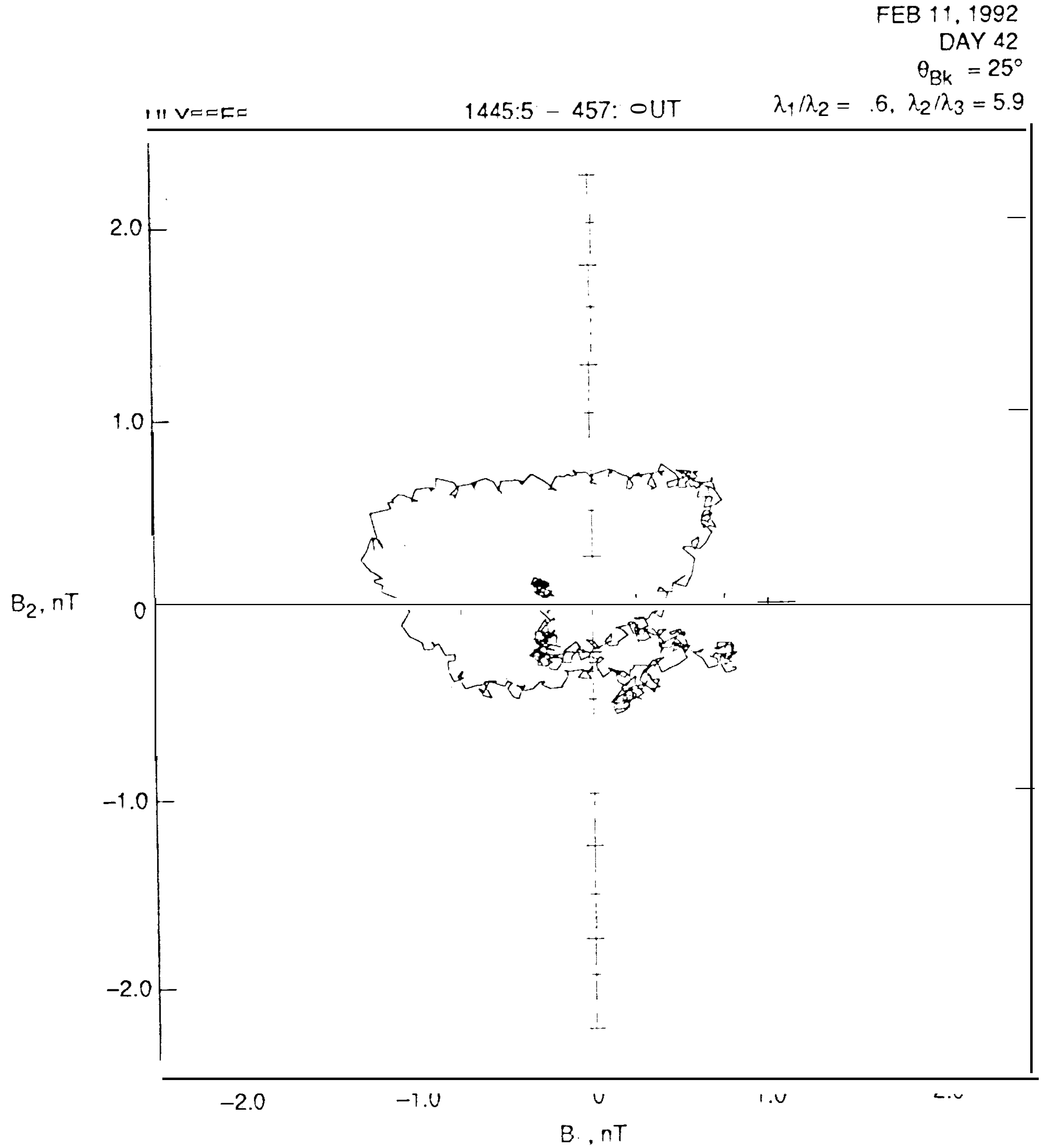
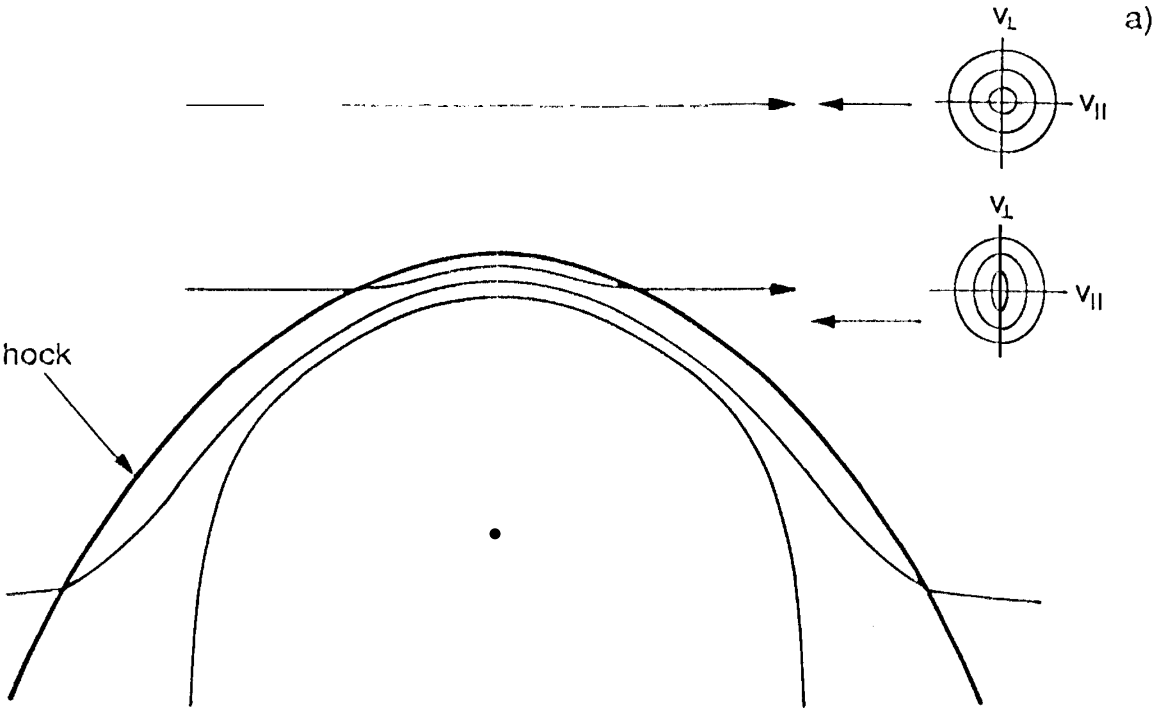
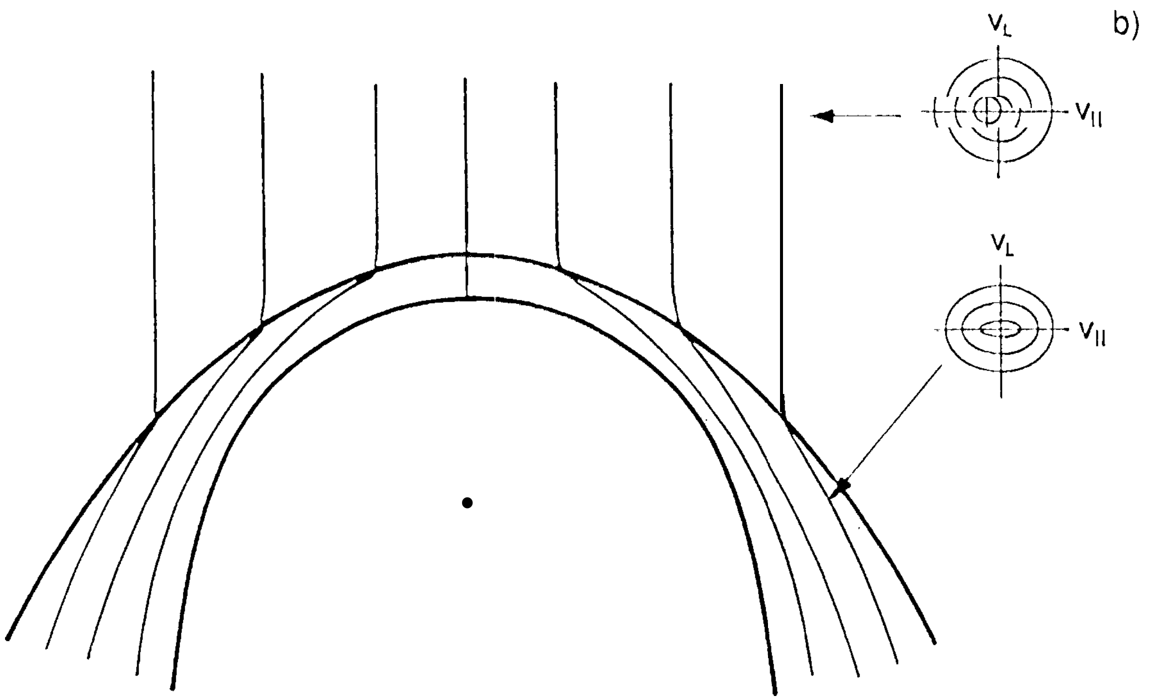

FEB 11, 1992
DAY 42
θ_{Bk} = 25°
1445:5 – 457: OUT
λ_1/λ_2 = .6, λ_2/λ_3 = 5.9
2.0
1.0
0
−1.0
−2.0
B_2, nT
−2.0
−1.0
B , nT

Fig. 11



a)
$v_\perp$
$v_\parallel$
$v_\perp$
$v_\parallel$
Shock



b)
$v_\perp$
$v_\parallel$
$v_\perp$
$v_\parallel$

Fig. 12